THE MECHANICAL PROPERTIES OF TERNARY AND QUATERNARY Ti_2NbAl-BASED TITANIUM ALUMINIDE ALLOYS

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Abstract

Ordered orthorhombic Ti_2NbAl-based titanium aluminide alloys have been found to have higher specific strength and fracture toughness with no loss in creep resistance relative to state of the art Ti_3Al-based alloys. The specific strength of some Ti_2NbAl-based (O phase) alloys was a factor of two greater than comparable Ti_3Al-base (α_2) alloys , and the O-phase alloys also had fracture toughnesses a factor of two higher. Quaternary addition of vanadium produced a room temperature tensile elongation of 18.8%. These vanadium-modified O-phase alloys had higher strength, better creep resistance and greater ductility than state of the art super-alpha titanium alloys.

Introduction

The low density and high strength of titanium aluminide alloys has made them attractive for elevated temperature aircraft and aerospace applications. Although the Ti_3Al-based titanium aluminide Ti-24Al-11Nb has sufficient room temperature fracture toughness for engineering trials, higher fracture toughness and creep resistance have been needed to stimulate wider scale replacement of superalloys by titanium aluminide alloys [1, 2]. Higher specific strength and creep resistance titanium aluminides have been developed, but at the expense of room temperature fracture toughness [2-4]. It was found that the recently identified ternary ordered orthorhombic Ti_2NbAl O phase have both higher specific strength and higher room temperature fracture toughness than Ti_3Al-based alloys [5-7].

The crystal structures of the Ti_3Al (α_2) and Ti_2NbAl (O) phases are similar [8, 9]. The ordered orthorhombic Ti_2NbAl structure has a Cmcm symmetry and is only a slight distortion of the D019 structure . It differs in that one of the titanium subsites in the D019 structure is preferentially occupied by Nb in Ti_2NbAl and randomly occupied by Nb and Ti in Ti_3Al [8-10]. A distinct Ti_2NbAl phase field has been established near 25 at.% Al with Nb content

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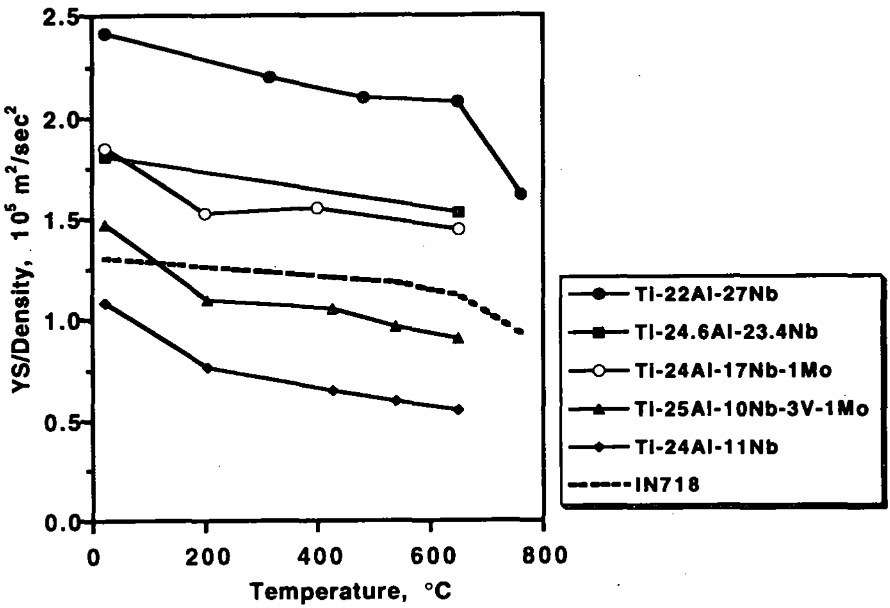

Figure 1. Specific yield strength of Ti-22Al-27Nb and Ti-24.6Al-23.4Nb relative to other titanium aluminide alloys and IN718.

ranging from approximately 16 to 30 at.% Nb [11]. Lower aluminum alloys like Ti-22Al-27Nb have been shown to lie in a two phase O + β_O phase field [6].

Mechanical Property Comparisons: The specific yield strength (ratio of yield strength to density) of several titanium aluminide alloys and the high strength wrought superalloy IN718 are shown in Figure 1.[2, 4, 6, 12, 13]. It can be seen that the ordered orthorhombic titanium aluminides such as Ti-22Al-27Nb and Ti-24.6Al-23.4Nb have a considerable strength advantage over nickel-base superalloys and other titanium aluminides from room temperature to 650°C. The tensile strength of Ti-22Al-27Nb was 1290 MPa at 650°C. Tensile curves of Ti-22Al-27Nb are shown in Figure 2. Ti-22Al-27Nb had good tensile elongation between room temperature and 650°C.

In the direct aged condition, corresponding to the data in Figures 1 and 2, Ti-22Al-27Nb had a microstructure fine Widmanstatten O+β_O transformation structure with a low volume fraction of prior O phase [6]. Ti-24.6Al-23.4Nb also had a two phase O+β_O microstructure, but with a very low volume fraction of β_O phase. It was not as strong as Ti-22Al-27Nb, but it had comparable room temperature tensile elongation. Greater dislocation homogeneity more of non-basal slip activity has been observed in Ti_2NbAl than in Ti_3Al [14]. This may account for the ductility of the nearly single O phase alloy Ti-24.6Al-23.4Nb at room temperature.

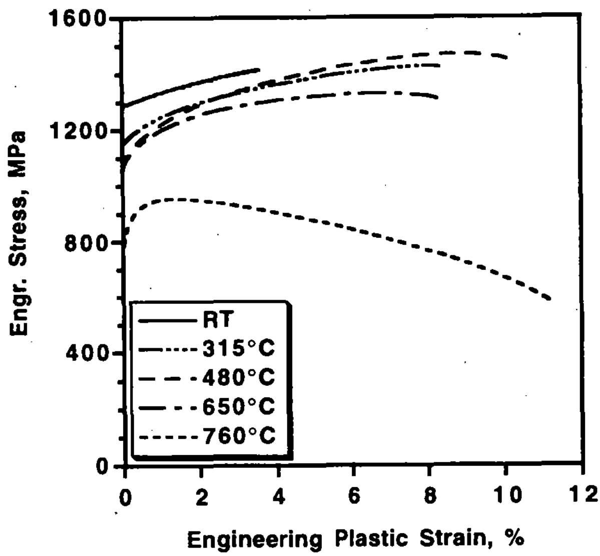

Figure 2. Engineering stress vs engineering plastic strain curves for Ti-22Al-27Nb.

Figure 3 is a compares the creep lifetime, room temperature tensile elongation and fracture toughness for several titanium aluminide alloys [15]. It shows the trade-off between creep resistance and low temperature ductility and fracture toughness for these alloys. The alloys, Ti-24Al-17Nb-1Mo, Ti-25Al-10Nb-3V-1Mo and Ti-25Al-8Nb-2Ta-2Mo all had 0.2% creep lifetimes of from 3 to 4 hrs at 650°C/315 MPa. Their fracture toughnesses were low, ranging from 14 to 19 MPa√m; lower than that of Ti-24Al-11Nb which was 25 to 27 MPa√m. Beta heat treated Ti-24.6Al-23.4Nb which consisted of the ordered orthorhombic O phase, also fit into the first group, but represented a large improvement in 0.2% creep lifetime relative to the Ti_3Al-based alloys. Its ductility at room temperature was 1.3%.

The higher fracture toughness alloys Ti-24Al-17Nb-0.5Mo and Ti-22Al-27Nb made up a second group. The fracture toughness of Ti-24Al-17Nb-0.5Mo was 26 MPa√m, but its 0.2% creep lifetime of was only 1.3 hrs; less than that of the first group of alloys. It sacrificed creep resistance for higher fracture toughness. Ti-22Al-27Nb in the as heat treated and heat treated plus aged condition [5, 6] had fracture toughnesses of from 26 to 31 MPa√m, respectively, but creep lifetimes as high or higher than that of the creep resistant alloys Ti-24Al-17Nb-1Mo, Ti-25Al-10Nb-3V-1Mo and Ti-25Al-8Nb-2Ta-2Mo. The 0.2% creep lifetime of Ti-22Al-27Nb at 650°C, 315 MPa was 4 hrs direct aged and 6 hrs after additional aging for 100 hrs at 760°C. The ternary ordered orthorhombic Ti_2NbAl-based alloys therefore achieved an increase in fracture

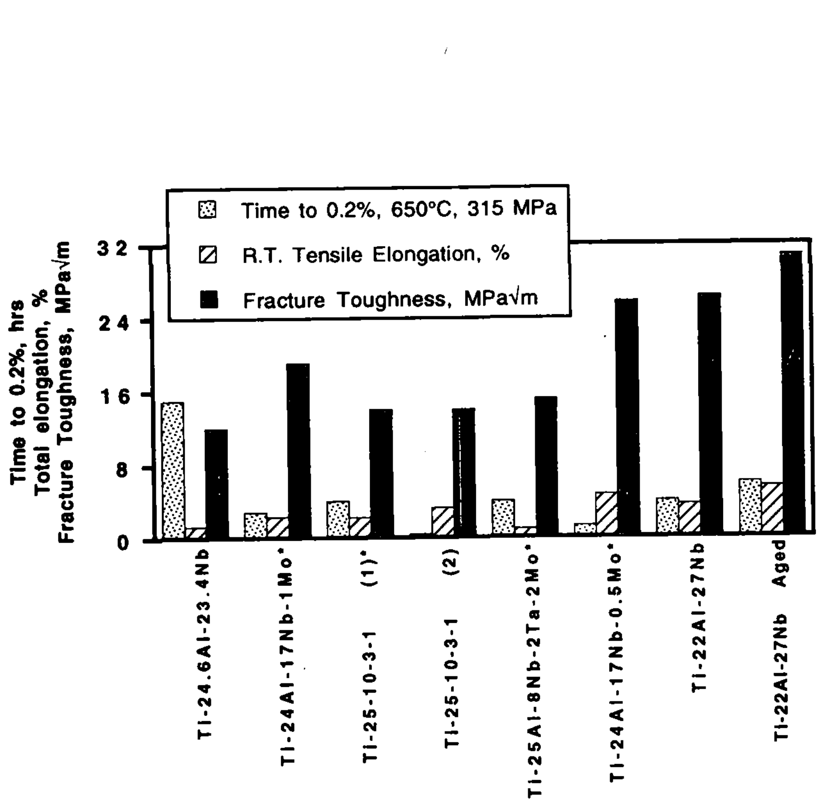

Figure 3. Comparison of the time to 0.2% creep strain at 650°C, 315 MPa (interpolated for the samples identified by an asterisk), total tensile elongation and fracture toughness of titanium aluminide alloys.

toughness and strength without the sacrifice in creep resistance characteristic of high fracture toughness Ti_3Al-based alloys.

Effect of Vanadium Alloy Additions: The effect of quaternary vanadium additions to Ti_2NbAl-based alloys was also studied. Vanadium additions produced a slight increase in the volume fraction of β_o phase for a given aluminum content, but there was evidence of vanadium alloying in both the β_o and O phases. Ti-23.6Al-22.9Nb-1.0V, which was heat treated at 1200°C/2 hrs + 900°C/600 hrs and water quenched, had approximately 50 v/o ordered orthorhombic laths in a β_o ordered beta matrix. The vanadium contents of the β_o and O phases were approximately 1.3 at.% and 0.7 at.%, respectively.

Large increases in the room temperature ductility were produced by quaternary vanadium additions. Table 1 shows tensile properties of ternary and vanadium-substituted quaternary Ti_2NbAl-based alloys. Room temperature tests were conducted in air; 650°C tests were in vacuum. The strain rate was $7x10^{-4}$/sec.

Addition of 5 at.% V to a Ti-22Al-25Nb base alloy increased the room temperature tensile ductility from 3.6% to 18.8% for direct aged samples. The microstructure of direct aged Ti-21.5Al-20Nb-5V consisted of a Widmanstatten

Table 1. Tensile properties of Ti-Al-Nb and Ti-Al-Nb-V alloys.

Alloy and Heat Treatment	TEST TEMP (°C)	0.2% YS (MPa)	UTS (MPa)	%El @ Failure
Ti-21.9Al-24.1Nb	R.T.	1257	1350	3.57
815°C/4hr	650	1049	1177	13.48
Ti-21.5Al-20Nb-5V	R.T.	900	1161	18.8
815°C/24hr+760°C/100hr	650	684	772	16.5
Ti-21.5Al-20Nb-5V	R.T.	750	943	12.5
1075°C+815°C/24hr+ 760°C/100hr	650	652	763	14.9
Ti-22Al-23Nb-1V				
815°C/24hr+760°C/100hr	R.T.	1092	1308	8.8

transformation structure of O laths in a β_0 matrix with some prior phase and allotriomorphic grain boundary phase, Figure 4. Its strength at room temperature and 650°C was lower than that of the ternary base alloy Ti-21.9Al-24.1Nb by 25 to 35%, indicating that ductility gains were at the expense of strength. The tensile strength of Ti-21.5Al-20Nb-5V was as high or higher than that of of Ti-25Al-10Nb-3V-1Mo or Ti-24Al-17Nb-1Mo at room temperature and 650°C, however [2-4].

Addition of 1 at.% vanadium also had an effect. The 8.8% room temperature tensile elongation of Ti-23.6Al-22.9Nb-1V was higher than that of the ternary base alloy Ti-21.9Al-24.1Nb. Its room temperature tensile strength was 1308 MPa, close to that of the base alloy which was 1350 MPa.

The room and elevated temperature tensile properties of the super-alpha titanium alloys IMI834 and Ti-1100 [16, 17] are tabulated in Table 2. Ti-21.5Al-20Nb-5V had nearly twice the room temperature elongation of both of these alloys, was stronger at room temperature, and was nearly twice as strong at 650°C.

The fracture toughness of a vanadium-modified Ti_2NbAl-base alloy, Ti-21.5Al-20Nb-5V, was determined using fatigue precracked bend samples. Two tests gave K_{IC} values of 29.3 and 30.8 MPa√m (an average of 30.1 MPa√m). This fracture toughness was comparable to values obtained for the high fracture toughness alloy Ti-22Al-27Nb.

The effect of vanadium on creep properties is shown in Table 3. The 0.2% creep lifetime for Ti-23.6Al-22.9Nb-1V at 650°C and 315 MPa was 2.1 hours compared to 6.1 hrs for Ti-24Al-23.3Nb. The alloy Ti-23.6Al-22.9Nb-1V had a lower volume fraction of O phase than Ti-24Al-23.3Nb, and the difference in creep behavior may be partly due to the relative properties of O and β_0 phases. The

Table 2. Tensile properties of super-alpha titanium alloys.

SAMPLE NUMBER	TEST TEMP (°C)	0.2% YS (MPa)	UTS (MPa)	%Elong Fail
IMI834, 1045°C+700°C	RT	959	1035	10.1
IMI834, 1045°C+700°C	650	543	651	15.6
Ti-1100, 590°C Direct Aged	RT	897	987	10.5
Ti-1100, 590°C Direct Aged	650	524	635	16.5

Table 3. Creep properties of ternary and quaternary Ti_2NbAl-based alloys at 650°C, 315 MPa.

Alloy	Heat Treatment	0.2%	1%
Ti-24Al-23.3Nb	1160C+815C	6.1	91.7
Ti-23.6Al-22.9Nb-1V	1075C+815C+760C	2.10	39.10

creep resistance of Ti-23.6Al-22.9Nb-1V was greater than that of Ti-24Al-17Nb-0.5Mo which had a 0.2% creep lifetime of 1.3 hrs under the same conditions.

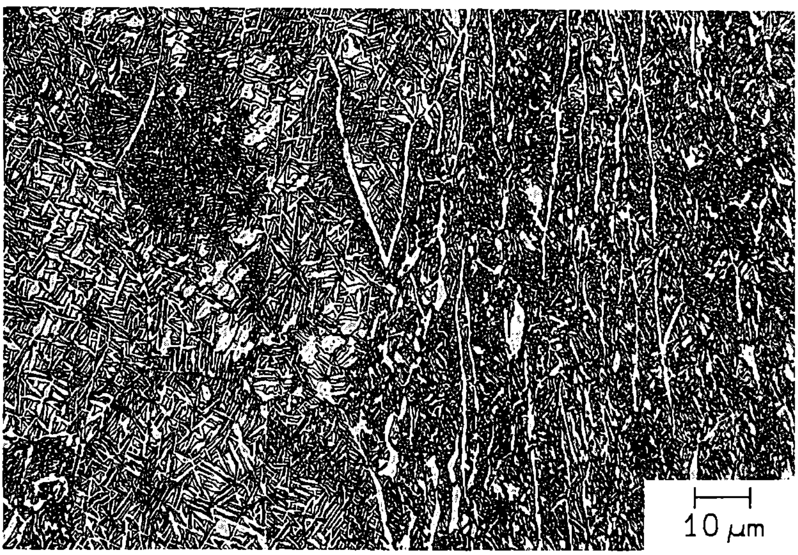

Figure 4. The microstructure of Ti-21.5Al-20Nb-5V after extrusion and a heat treatment of 815°C/24 hr + 760°C/100 hr.

Summary and Conclusions

The ordered orthorhombic alloys based on the titanium aluminide Ti_2NbAl represent a new class of titanium aluminide alloys which have higher strength and higher fracture toughness than current Ti_3Al-base alloys. Their most distinct characteristic was high specific strength relative to other titanium aluminide and nickel-base superalloys, but alloying with vanadium produced alloys with as much as 18.8% room temperature tensile elongation. Tensile elongation of this magnitude is usually associated with disordered titanium alloys rather than titanium aluminides. The flexibility that is associated with the breadth of properties available in these alloys suggest that many aircraft engine applications may be possible with slight modifications of composition or processing to tailor the properties for each application.

References

1. M.J. Blackburn and M.P. Smith, "Titanium Alloys of the Ti_3Al Type", U.S. Patent # 4,292,077,

2. D.P. DeLuca, *et al.*, "Fatigue and Fracture of Titanium Aluminides", Report # WRDC-TR-89-4136, U.S. Air Force, WRDC, February, 1990.

3. M.J. Blackburn and M.P. Smith, "Titanium Aluminum Alloys Containing Niobium, Vanadium and Molybdenum", U.S. Patent # 4,716,020, Sept. 27, 1982.

4. M.J. Blackburn and M.P. Smith, "Improved Toughness Alloys Based Upon Titanium Aluminides", Report # WRDC-TR-89-4095, U.S. Air Force, WRDC, October, 1989.

5. R.G. Rowe, *et al.*, "Tensile and Creep Behavior of Ordered Orthorhombic Ti_2AlNb-Based Alloys", Mat. Res. Soc. Symp. Proc, 213, 703-708, (1991).

6. R.G. Rowe, "The Mechanical Properties of Titanium Aluminides Near Ti-25Al-25Nb". in Microstructure/Property Relationships in Titanium Alloys and Titanium Aluminides. Edited by Y. Kim and R.R. Boyer, TMS, AIME, Warrendale, OH, 1990, 387-398

7. R.G. Rowe, "Recent Developments in Ti-Al-Nb Alloys", in High Temperature Aluminides and Intermetallics, Edited by C.T.Liu, S. H. Whang D.P. Pope and J.O. Stigler, TMS, AIME: Warrendale, OH. 1990, p. 375-401.

8. D. Banerjee, "A New Ordered Orthorhombic Phase in a Ti_3Al-Nb Alloy", Acta Met., 36 p. 871-882, (1989).

9. B. Mozer, *et al.*, "Neutron Powder Diffraction Study of the Orthorhombic Ti_2AlNb Phase", Scripta Met. et Mater., 24, 2363-2368, (1990).

10. L.A. Bendersky, W.J. Boettinger, and A. Roytburd, "Crystallography and Thermodynamics of Hierarchical Structures of $(Ti,Nb)_3Al$ Alloys", in Proceedings, Japan Inst. of Metals Intermetallics Symposium-6, Sendai, Japan, June 1991. To be published.

11. R.G. Rowe, *et al.*, "Phase Equilibria in Ternary Ti-Al-Nb Alloys Near Ti_2NbAl". in Proceedings, Seventh World Conference on Titanium, San Diego, CA June 1992. TMS-AIME, Warrendale, OH.

12. J.M. Larsen, *et al.*, "Titanium Aluminides for Aerospace Applications". in High Temperature Aluminides and Intermetallics. C.T.Liu, S. H. Whang D.P. Pope and J.O. Stiegler, TMS-AIME, Warrendale, PA, 1989, p. 521-556

13. "High Temperature, High Strength Nickel-Base Alloys", Report # The International Nickel Company, Inc. 3rd edition, July 1977.

14. D. Banerjee, R.G. Rowe, and E.L. Hall, "Deformation of the Orthorhombic Phase in Ti-Al-Nb Alloys", Mat. Res. Soc. Symp. Proc, 213, p. 285-290, (1991).

15. R.G. Rowe, "Advanced Ti_3Al-Base Alloy Property Comparison". in Synthesis, Processing and Modelling of Advanced Materials. ASM International, Paris, France. Sept. 1991, To be published,

16. "Ti-1100", Report # Titanium Metals Corporation, Henderson, NV, 1987.

17. "IMI834", Report # IMI Titanium Limited, Birmingham, UK., 1990.

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